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MYSTERIOUS LUNAR SAMPLES

Josef Zähringer

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MYSTERIOUS LUNAR SAMPLES[1]

Josef Zähringer~~[2][3]~~

ABSTRACT. The samples of lunar material obtained by the Apollo 11 and Apollo 12 space missions are discussed, and the significance of the investigations of these samples for the study of lunar geology and hypothesis of lunar origin is evaluated. The activities of the astronauts on the lunar surface are briefly considered. The lunar samples are described giving attention to minerals also present on Earth and to minerals not previously known. The chemical composition of lunar materials is discussed and compared with the composition of terrestrial and meteoritic materials. Searches for superheavy elements and other new elements are reported. Effects of meteorites, cosmic radiation, and solar wind on lunar material are discussed taking into account results obtained with some new investigative techniques. The determination of the age of lunar materials is considered, and hypotheses of lunar origin are examined in the light of the new information obtained. A71-19605.

Introduction

Development of space research has yielded completely new possibilities /170*
for the experimental investigation of space. By means of rocket and satellite

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*Numbers in the margin indicate pagination in the original foreign text.

(1) Public lecture, given during the general meeting of the Max Planck Society, June 10, 1970 in Saarbrücken.

(2) Prof. J. Zähringer died in an accident on July 22, 1970.

(3) Max-Planck-Institute for Nuclear Physics, Heidelberg

probes, processes in interplanetary space are continuously recorded. During the last ten years, we have in this way learned a great deal about our planetary system, and to some extent also about more distant objects.

But the object of space research is not only that of gaining knowledge about current processes. That would amount to nothing more than a snapshot, measured by the age of our planetary system. Essentially, we wish to know more about the origin of the planets and of our Earth in particular. We would like to pose the ambitious questions on the origin of our planetary system. But for this, one needs information from earlier times, from epochs which lie millions of years in the past.

Certainly such data are accessible only with great difficulty; and when they are available, they can only be fragmentary. Laboratory studies of meteorites have shown that they still contain measurable traces of the early history of the solar system. From this, we have learned that our planetary system is at least 4.6 billion years old. So far, meteroites have been the only extraterrestrial material available to us. It is conjectured that they originate from broken-up asteroids or from disintegrated comets, although we still do not know this exactly. We have, however, many well-founded indications that they cooled very early after the production of the planetary system. Thus, the relatively small, quickly cooled bodies are particularly interesting for research on the early history of the solar system. We hope to obtain quite similar information from lunar research. The satellite of our Earth, and the many other moons of the outer planets, are likewise small bodies which are presumed to have solidified quickly. Thus, we can hope that primitive plane- /171
tary material is still to be found on their surfaces. This is the reason for scientists' great interest in lunar research. They consider the adventurous trip to our satellite as a kind of "archeological expedition".

In the last year, American astronauts have twice landed on the Moon. They have collected Moon samples and returned them to the Earth. Since then, these samples have been studied thoroughly. At the beginning of January, 1970, about

1,000 scientists reported their results at a meeting in Houston. The reports were printed in "Science," Volume 167, of 30 January, 1970.

The desire to visit our neighboring heavenly body is probably as old as mankind itself. The Moon is so near the Earth, and it changes its phases so rapidly, that people have always given it as much attention as the Sun. This is expressed in many names, customs, and religious observances.

Eclipses of the Moon are some of the oldest astronomical phenomena recorded in history. Anaxagoras (ca. 500 BC) was the first to explain them correctly, after Thales of Miletus had found the cause for the phases of the Moon. Ptolemy had great difficulty with the orbit of the Moon, although it should have fit quite well into his geocentric system. But he had to assume a complicated mechanism to explain the most striking irregularities of the lunar orbit.

Galileo was the first scholar to study the surface structure of the Moon. Galileo discovered the telescope in 1609, simultaneously with Kepler's explanation of planetary motion. With the telescope he made a series of sensational astronomical observations. He reported on his first observation of the Moon: "I saw the Moon as close as if it were only twice the diameter of the Earth away. The side turned toward us is in parts much brighter, and in parts much darker. The surface is neither smooth nor uniform, nor spherical, as is assumed by many philosophers. It is rough, with hollows and bulges, nothing other than the Earth distinguished by mountains and valleys. This has never been seen by anyone before me." (Siderius Nuncius, see Figure 1).

Galileo's observations were soon improved, and the Danzig astronomer Hevelius produced one of the first reliable lunar maps (Figure 2, left). He still used designations from the Earth's geography. Pater Riccioli changed this nomenclature, because he recognized no relations to Earthly shapes. He gave /172
the seas romantic names (Serenity, Dreams, Fecundity, Calm, Storms, etc.) while he provided the mountains with the names of great men (Figure 2, right). He understood the vanity of humans; his designation has persisted to today.

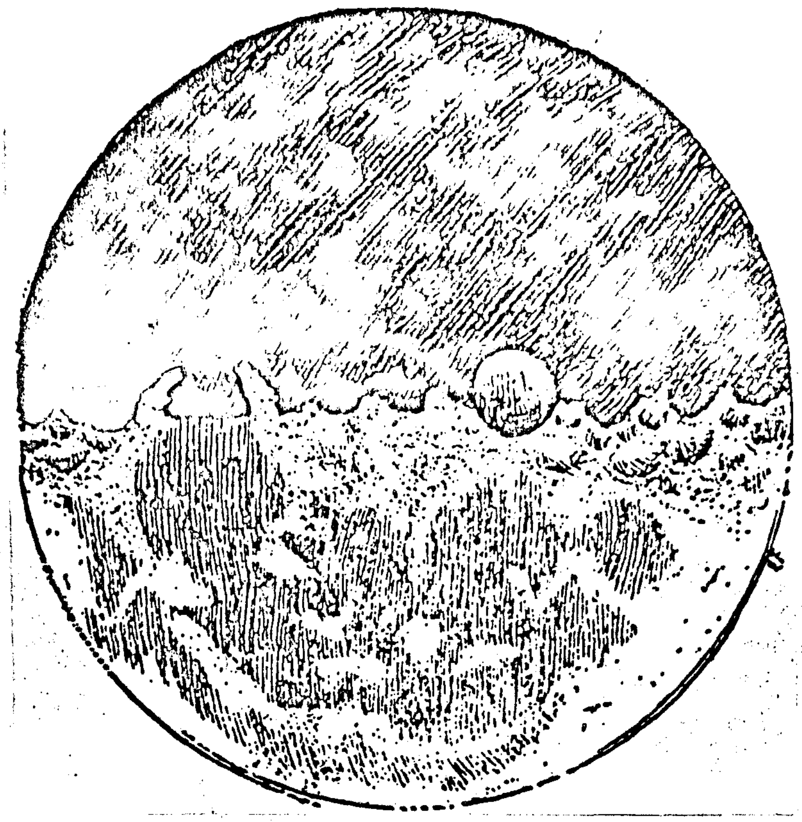

Figure 1. A sketch of Galileo's observations of 1609, which he made with the telescope which he had just discovered.

From the irregular shadowing, he calculated the height of the lunar mountains as about 10 km. He had also observed ringed mountains and plains.

Apollo Missions

The landing sites of Apollo XI and XII are flat, mare regions (Figure 2). They are covered with a dust layer, in which small rock fragments are scattered. The dust layer is interspersed with many craters of up to 100 m diameter, usually flat and filled up. Larger rock fragments, and some glass fragments appear on the floors of some deeper craters. Presumably these are primitive /174
rock. On the crater walls, the thickness of the dust layer can be estimated

Figure 2. The left Moon map is derived from the Danzig astronomer Hevelius, who borrowed designations from geography on Earth. The right map contains the revised names by Pater Riccioli. This nomenclature has persisted to the present.

as 4-6 m. Figure 3 shows such a crater landscape in the Sea of Storms. Irregular rock fragments are imbedded in the crater walls, just as on the surface.

The astronauts had many missions during their Moon visit. First, they quickly filled a plastic bag with dust and stones from near the landing site, so that they could bring back at least some Moon samples in case of an unplanned early departure. Then the astronautes set up experiments, including a seismometer, with which something can be learned about the internal structure of the

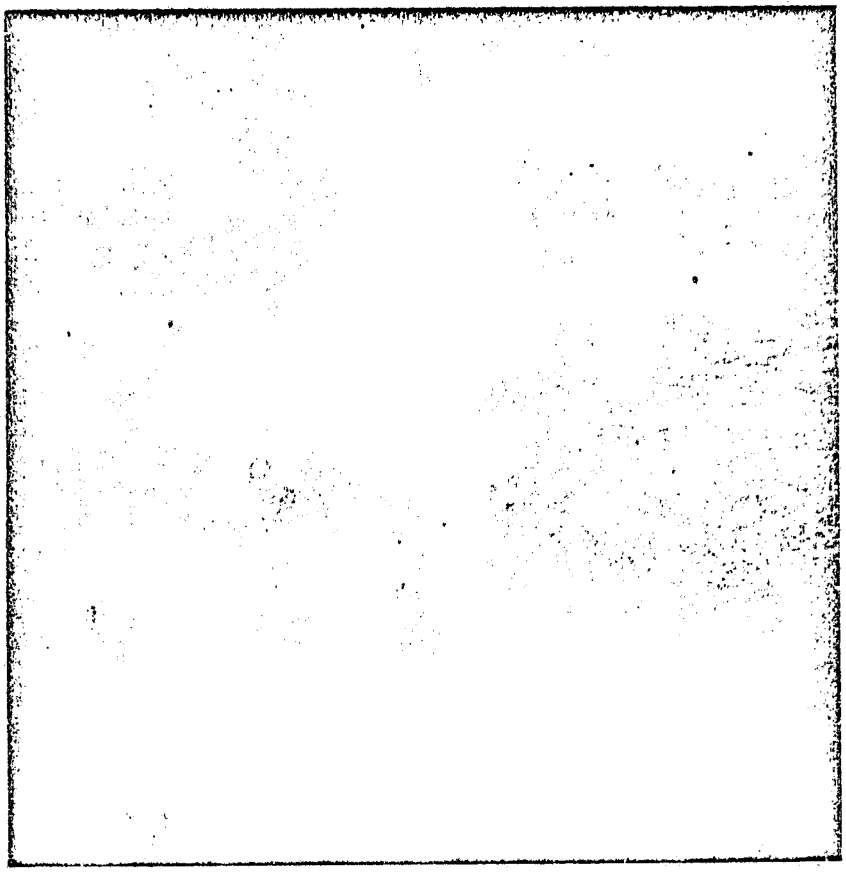

Figure 3. A crater landscape near the landing site of Apollo XII. Rock fragments appear on the floor of the crater. Presumably they are primitive rocks. The diameter of the large crater is about 100 m.

Moon. Figure 4 shows the experiments set up near the landing site of Apollo XII. The lunar vehicle and the third stage of the Saturn rocket which struck the Moon started lunar vibrations which persisted for hours. This phenomenon is not yet entirely explained. It appears as if the upper lunar crust, about 10 km thick, had broken up. The waves then suffered this time delay due to /176
multiple reflections by the rock fragments. Ditches were dug, so as to become acquainted with the nature of the ground. Drill cores up to 40 cm long were also brought back, in order to detect different deposits through possible inhomogeneities. This showed that the ground below 10 cm depth was very hard.

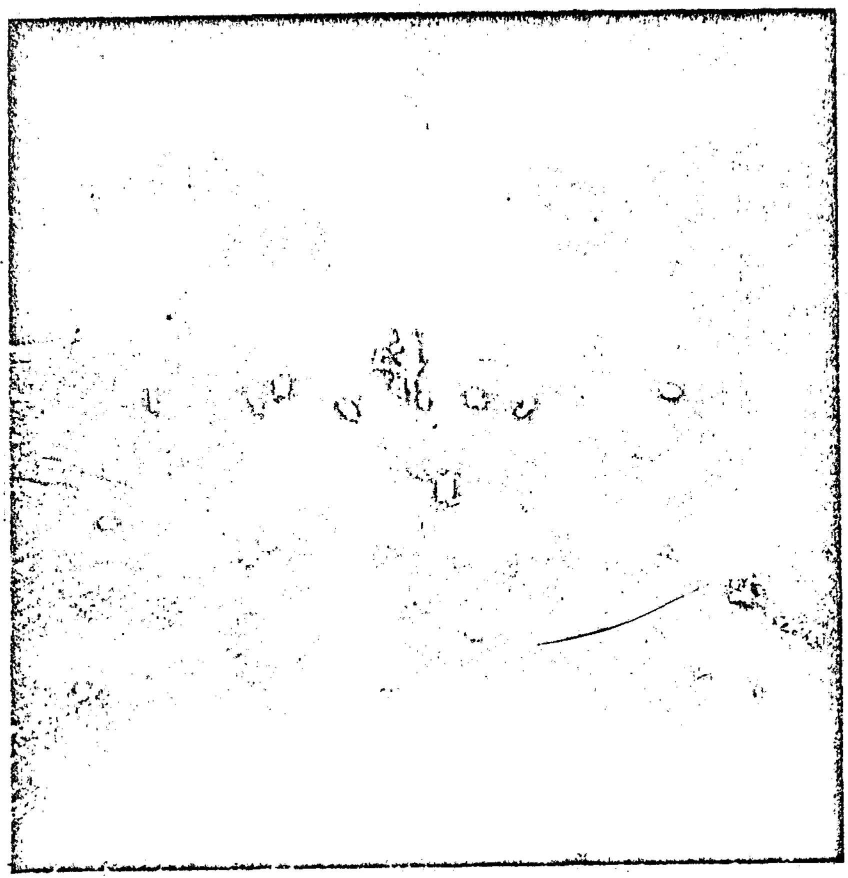

Figure 4. The experiments set up near the landing site of Apollo XII (seismometer, magnetometer, solar wind spectrometer, pressure-measuring device, and ion detector). The experiments are supplied from a nuclear thermal source, and the results are telemetered to Earth.

The legs of the lunar lander sank only 8 cm into the Moon dust. The footprints of the astronauts are only a few centimeters deep. Clods fell out of the tracks and did not break up. Even the drill holes did not collapse after removal of the cores. Apparently the adhesion forces bake the dust hard in the ultra-high vacuum of the lunar surface.

Arrival of the Lunar Samples

From the Apollo XI mission, the astronauts (Armstrong, Aldrin, and Collins) brought back 11 kg of dust and 11 kg of rocks to the Earth. With Apollo XII the yield was 3 kg dust and 45 rocks weighing 31 kg. With respect to study of the lunar samples, the National Academy of Sciences had concluded in 1964 to test them for pathogenic characteristics for six weeks in quarantine. For this purpose, a lunar laboratory with the necessary technical equipment was erected at the Manned Space Flight Center in Houston. During the quarantine time, time-critical experiments such as measurement of short-lived radioactivity, and temporary studies, were to be performed there.

For the various detailed measurements, 140 Principal Investigators (P. I.) were sought out. Many of these were not Americans. The scientists selected had for the most part previously worked with meteorites and were accustomed to working with small amounts of material. The questions for the lunar samples were similar to those for meteorites. Thus, the experimental equipment was already developed and available.

On the basis of an invitation from O. A. Schaeffer (State University of New York, Stony Brook), the author had the opportunity to cooperate in the provisional analyses in Houston and to experience this unique historical event. The arrival of the Apollo XI samples was quite exciting. There were problems among the scientists — Who dared chance the first historic look? When the sample holders were finally opened and the rocks appeared, to be sure, one saw /177 only disappointed looks. The rocks looked like a pile of coke. They were covered with a layer of very fine dust and showed no mineralogical details.

The provisional analyses had to be performed in a high vacuum chamber or in closed glove boxes until it could safely be concluded that this material contained no dangerous "Moon bacteria". (This danger was only slight, to be sure, because about 30 tons of extraterrestrial material fall on the Earth every day, including some meteorites, without any great biological catastrophe having yet occurred.)

Occasionally a glove broke, or a line to the sample chamber, and the scientists in the direct neighborhood were "endangered" — including the author — and had to join the astronauts in the quarantine station. Direct contact with the astronauts was very advantageous for identification of the rock samples, because they could answer many questions fresh from memory. In discussions with the astronauts, one could see their broad training and special abilities. Usually they behaved like test pilots who had mastered many dangerous situations through quick action. "The flight to the Moon was a work week like any other". These men could also obey orders. An arbitrary operation would put the control center out of order. In particular, they are quite normal, very pleasant, and extremely humorous men. Charles Conrad declined an invitation to play poker: "I've already lived dangerously enough; I can't afford poker."

After conclusion of the preliminary studies, the samples were distributed to the various institutes.

Four principal investigators and their co-workers from two Max Planck Institutes participated in this program: Professors H. Hintenberger and H. Wänke (Max Planck Institute for Chemistry [Otto Hahn Institute], Mainz), and Professor P. Ramdohr and the author (Max Planck Institute for Nuclear Physics, Heidelberg). Professor W. Herr (University of Cologne), who was previously active at Mainz, and Professor W. v. Engelhardt (University of Tübingen) were other German participants.

The heavy participation of our society is related to the fact that it has a long tradition for frontier areas of cosmochemistry, and our society is associated with scientists. F. Paneth and W. Gentner have pressed forward with meteorite studies, and have also developed radioactive dating methods. Otto Hahn and J. Mattauch were the first to find radiogenic ^{87}Sr, which became the basis for the important Rb/Sr age determination method.

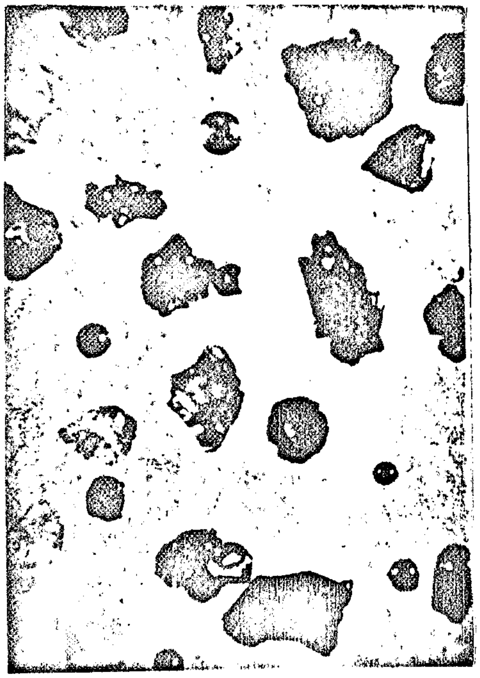

Figure 5. Moon dust under the microscope. The black grains are ilmenite, $FeTiO_3$. Pyroxene is dark brown. The light grains are feldspar or glass fragments. Foamy glass can be seen at the upper left. The spherical particles of different colors are glass.

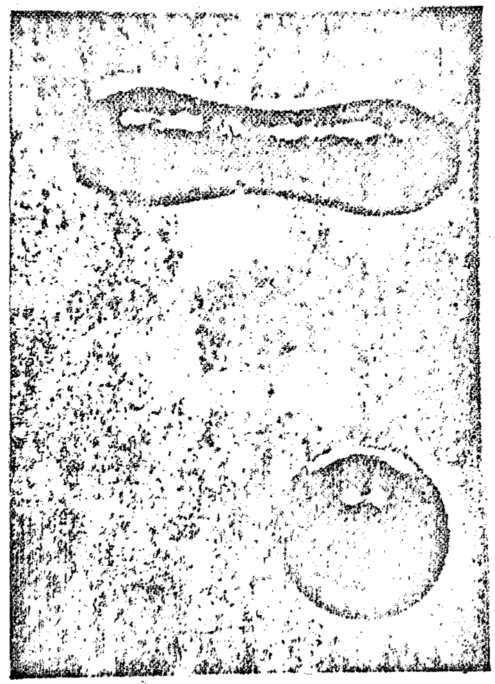

Figure 6. A dumb-bell shaped glass particle which has rotated in flight.

Description of the Lunar Samples

The lunar dust is very fine-grained, and looks like graphite powder. It contains glass as well as minerals. The major minerals are pyroxene, plagioclase, and ilmenite (Figure 5). The components are in part very strongly intergrown, and the glass is often foamy. In part, they show shock wave effects, indicating a complex history. Along with glass fragments, there are pretty glass spherical particles derived from meteorite impacts. On impact of bodies with velocities of many km/sec, the rock is vaporized, and — at a more distant zone — melted. The little glass spheres are either condensed from the silica vapor, or they are spray from the melted rock. Many glass particles which have rotated before solidification in flight have dynamic shapes. Ellipsoidal shapes, dumb-bells, and even tear-drop shapes were found. The latter result from the pulling apart of rapidly rotating dumb-bells. Typical glass particles can be seen in Figure 6. They are very reminiscent of the shapes of tektites produced by impacts on the Earth (see W. Gentner, 1964 Yearbook [1]). The chemical compositions of the individual glass particles vary strongly because they arise from different phases of condensation or from different rock types. The crystalline components of the dust derive their chemical composition, as well as their mineral makeup, from the crystalline rocks.

The crystalline rocks are basalt-like magmatic rocks. Their major minerals are likewise pyroxene, plagioclase, ilmenite, and olivine. They are all finely crystalline and full of bubbles, with a density of 3.4 (mean density of the Moon 3.34!). The bubbles are round, rarely oval, and have a diameter of 1-3 mm. The bubble wall is lined with strongly reflecting crystals. The voids make up as much as 15% of the volume. The largest crystals are of olivine, and are up to 0.5 mm in size. Otherwise, the grain sizes are between 0.01 and 0.2 mm. Other crystalline rocks are coarse-grained (0.2 to 3 mm) and have a density of 3.2. Irregular voids occur instead of bubbles. The voids extend into the crystals (Figure 7).

The agglomerates are easily frangible rocks made up of Moon dust and various crystalline fragments baked together. The individual components are often permeated with porous glass. Most of the crystalline fragments are smaller than 5 mm, and more abundant than the total of the magmatic rocks. Fragments from other deposits are often mixed in (Figure 8).

These descriptions apply for both landing sites, Apollo XI and XII, although there are noteworthy mineralogical differences. The rocks from Apollo XII (Sea of Storms) show a more varied mineral composition than those from Apollo XI. Many rocks from Apollo XII have a distinctly high content of pyroxene, plagioclase and olivine. Olivine was very rare in the Apollo XI

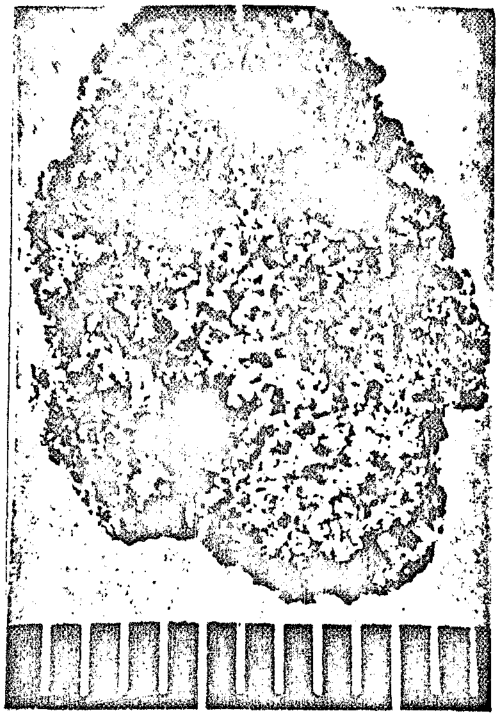

Figure 7. A crystalline Moon rock. Mineral composition: feldspar, pyroxene and ilmenite. These rocks are basalt-like, very finely crystalline, and have bubbles or voids.

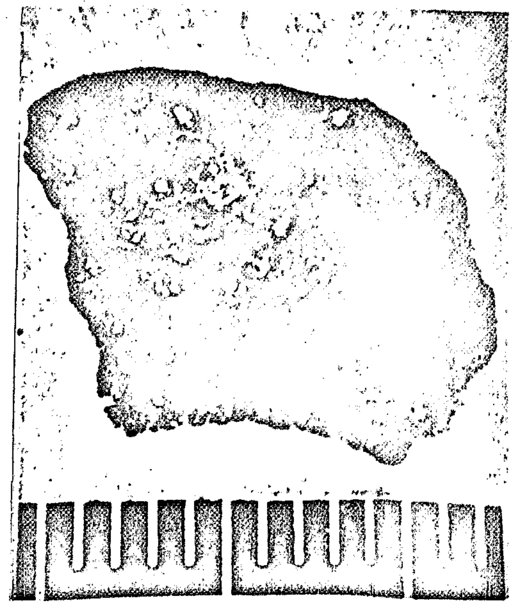

Figure 8. A sawed-up Moon agglomerate of bright crystalline stone fragments and Moon dust baked together.

samples. The two discovery sites even differ in the crystal sizes. Several Apollo XII rocks have crystals as large as 35 mm. Either the Apollo XII sampling was better directed because of the longer collecting time, or the rocks in the Sea of Storms are more strongly differentiated — that is, they have cooled more slowly from a larger sea of magma. It is also noteworthy that the Apollo XII rocks contained only 3 agglomerates, while half of them were agglomerates for Apollo XI.

With Apollo XI, a total of 12 minerals were found. They were:

Pyroxene	(Ca, Mg, Fe) Si_2O_6
Plagioclase	(Ca, Na) $Al_2Si_2O_8$

Ilmenite	$FeTiO_3$
Ulvospinel	Fe_2TiO_4
Pyroxyferroite	(Mg, Fe, Ca) SiO_3 (new)
Armacollite	(Mg, Fe) Ti_2O_5 (new)
Dysanalyte	$CaTiO_3$ (with 10% rare earths)
Tridymite	SiO_2
Cristobalite	
Rutile	TiO_2
Olivine	$(Mg, Fe)_2SiO_4$
Baddeleyite	ZrO_2
"Silicate"	Zr, Ti, Fe-silicate (new)

Three of these minerals had not previously been known on the Earth. Two of them were also found by P. Ramdohr and A. El Goresy [2] at the Max Planck Institute in Heidelberg. The (Mg, Fe)Ti_2O_5 was named armacollite after the Apollo XI astronauts (Armstrong, Aldrin, Collins) (Figure 9). Meteoritic minerals are also present, but they make up less than 1% by weight.

The Chemical Composition

The major components at three different sites on the lunar surface were known even before the Apollo landings. Turkevich and co-workers [3] flew alpha ray backscattering experiments on the soft-landed surveyor V, VI, and VII probes. The results were telemetered to Earth. An alpha emitter /182
irradiates the lunar surface, and the energy of the reflected alpha particles is proportional to the mass of the target nuclei. With calibration measurements, the major chemical components can be determined from the energy spectrum of the back-scattered alpha particles. To be sure, the results were decided to be correct only after they could be directly compared with laboratory results, and it was found that they showed distinct agreement.

Table 1 contains the Surveyor analyses and the results of the dust samples from Apollo XI and XII. The results from the mare samples differ

Figure 9. A highly polished section under the microscope. The bright lamellae are ilmenite; pyroxene is light gray; feldspar is dark gray. The large dark gray mineral grains (0.15 mm long) are armacollite, one of the minerals newly discovered in the Moon rocks [2].

only slightly. The Sea of Storms has only 3.5% TiO_2 and thus somewhat more MgO. All the other components are the same. The analysis in the highland at Tycho yielded only half as much iron and considerably less titanium, and so more aluminum and calcium [4].

The chemical composition indicates that we are dealing with a basic, i.e., silica-poor, magmatic rock which outwardly resembles Earth basalt, but is very different in its chemical composition.

The complete laboratory analyses of the Apollo XI samples naturally provide a much more extensive view into the chemistry of the lunar surface. The analyses of various crystalline rock samples showed no great differences.

TABLE 1. THE MAJOR COMPONENTS OF THE PREVIOUS SURVEYOR AND APOLLO LANDING SITES. THE CHEMICAL COMPOSITION OF THE SEAS IS RATHER SIMILAR, WHILE THE MOUNTAINS SHOW HIGHER ALUMINUM AND CALCIUM CONTENT (FELDSPAR) AND LESS TITANIUM AND IRON.

	Seas				Highland
Percent oxide by weight	Sea of Tranquillity		Sea of Storms	Sinus Medii	Tycho Crater
	Surveyor V	Apollo XI (dust)	Apollo XII (dust)	Surveyor VI	Surveyor VII
SiO_2	46	42	42	49	46
Al_2O_3	14	13	14	15	22
CaO	15	12	10	13	18
FeO	12	16	17	12	5.5
TiO_2	7.6	7.0	3.1	3.5	~ 0
MgO	4.4	7.6	12	6.6	7.0
Na_2O	0.6	0.5	0.4	0.8	0.7
K_2O	—	0.14	0.18	—	—

Only K, Rb, Cs, Ba, Th and U are less abundant in the coarsely crystalline rocks than in the finely crystalline ones, by a factor of about 2. /183

In all the samples, the easily volatilized elements such as the alkalis, Bi, Hg, Zn, Cd, Pb, Te, Ge and Br and Cl, as well as the siderophile elements Ni, Pd, and Au with distinct metallic character, are strongly depleted. The H_2O and carbon concentrations are also very low, amounting to only 10 to 100 ppm (ppm = 1 part in 10^6).

"Fireproof" elements which form resistant oxides, such as Ti, Zr, Sc, Sr, Hf, Y, and the rare earths are unusually abundant. In Figure 10 the principal elements, and in Figure 11 some typical trace elements are plotted and compared with averages from the Earth's crust, with ordinary chondrites, and with tektites. Enrichments or depletions up to a factor of 100 are

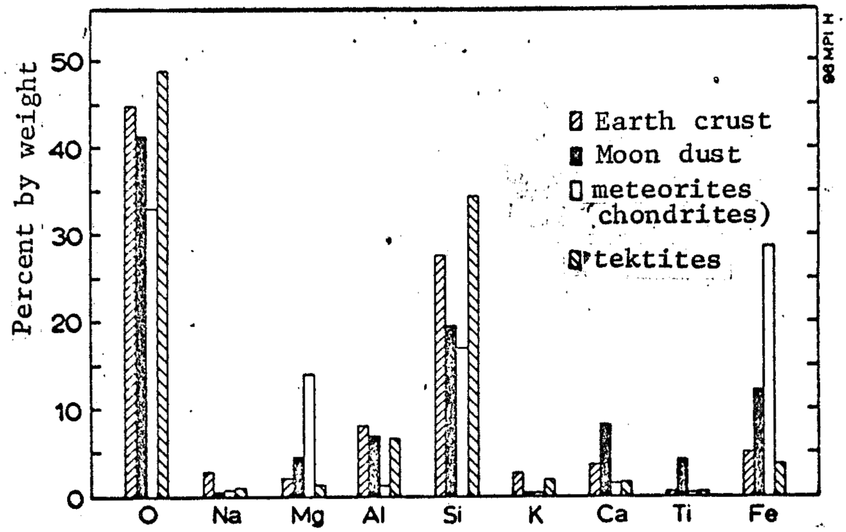

Figure 10. The abundances of the principal elements of the Moon dust are compared with the average for the Earth's crust, with chondrites, and with tektites.

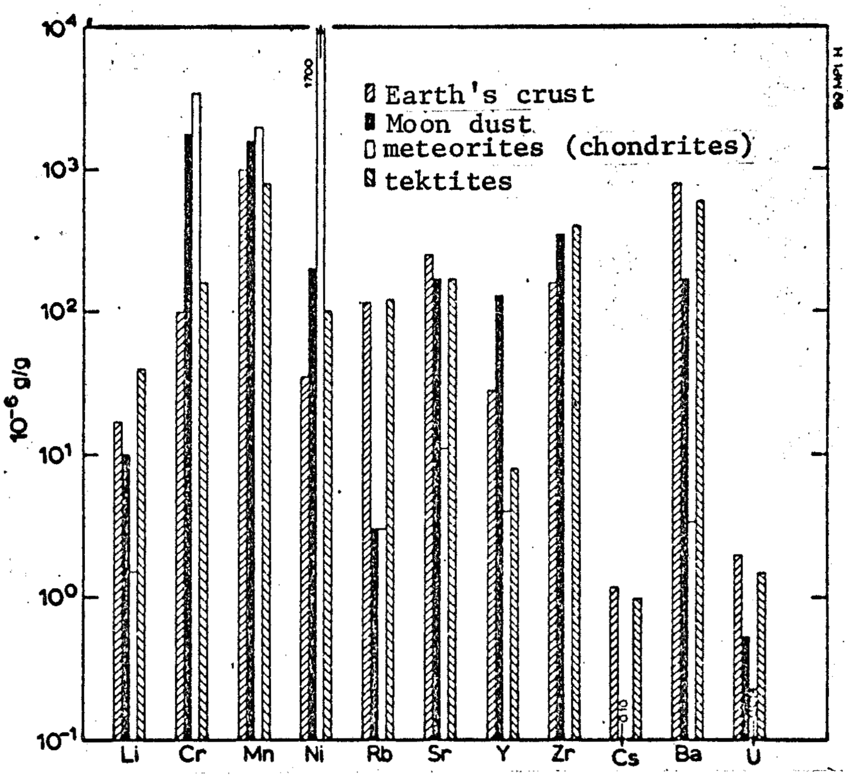

Figure 11. The same comparison as in Figure 10, for some typical trace elements. Note the logarithmic scale in this graph.

clearly visible. From this it is rather certain that chondrites and tektites cannot arise from the lunar surface.

Within the meteorite groups, a similar tendency toward enrichment of the poorly volatile elements can be detected in the transition from carbonaceous chondrites to the achondrites, which most nearly approach the eucrites of the Moon samples. Thus, one can conjecture that similar fractionation processes have taken place in the meteorites. The law of "geochemistry" which we have previously relied on cannot be applied in every case. The absence of water plays a major part in this.

The chemical composition is not yet understood. Beyond that, it must differ from that of the lunar interior. This appears merely from the densities of the rocks, which are between 3.2 and 3.4, depending on the bubble content, while the mean density of the Moon is only 3.34. Since the pressure of about 50 kb in the interior of the Moon causes a density increase of about 20%, the material in the interior of the Moon must consist of correspondingly less dense material than the Moon rock brought back so far. Here we have the rare phenomenon, that on the lunar surface, heavy rocks rest on a relatively light foundation. For a body which had been melted throughout, like the Earth, the heavy material occurs in the core, just the opposite from the /185 Earth.

Such mass enrichments — so-called mascons — had been found even earlier in the lunar surface. Satellites around the Moon show irregularities in their orbital motion, especially when passing over the circular maria. Thus, it is conjectured that impacts are responsible for these anomalies. Was the density of the impacting body higher? Did the impact energy of the projectile (asteroids or comets) cause the chemical fractionation? We can still give no answer to all these questions.

We must mention another special anomaly in the abundances within the rare earths. In all the Apollo XI samples, europium is rarer than the other rare earths, in comparison with chondrites, by a factor of about 4 (Figure 12).

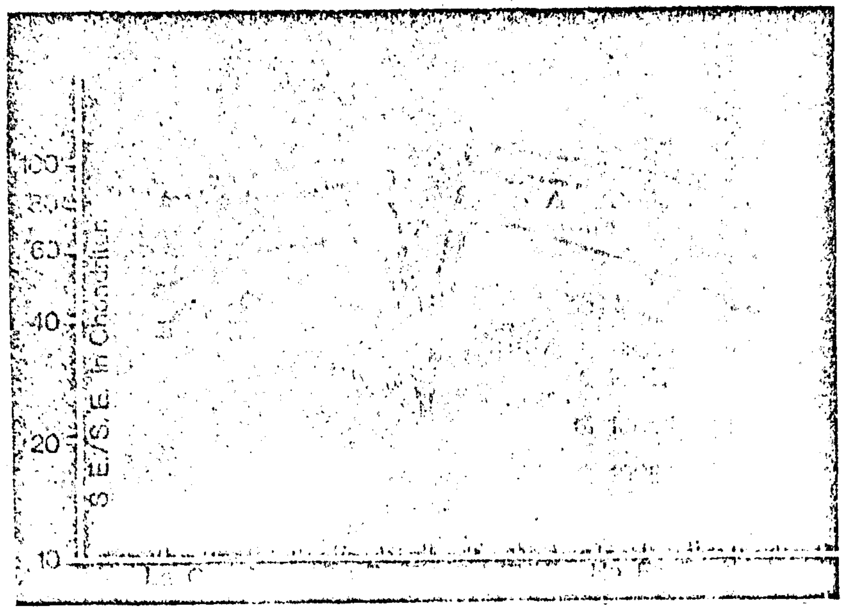

Figure 12. Abundance of the rare earths relative to chondrites. Like the poorly volatile elements (Ti, Y, Zr, etc.), they are highly enriched. The relatively small europium content indicates that there has been fractional crystallization at an extremely low degree of oxidation [11].

Under strongly reducing conditions, europium can also form bivalent compounds and be taken up by plagioclase, while all the other rare earths are only tri-valent in pyroxene. The oxygen partial pressure for this magmatic system is estimated as less than 10^{-13} atm [5].

Residues of meteoritic material are found in lunar dust and agglomerates. /186 Ni, Cd, Zn, Ag, Au, Lu, and Ta are more abundant than in crystalline rocks [6]. Addition of 2% or 10^{-9} grams of meteoric material per year in the form of carbonaceous chondrites can explain this difference. This bombardment rate agrees well with that estimated for the Earth. It corresponds to a daily incidence of about 30 tons of extraterrestrial material.

Along with less Ti, the Apollo XII samples also contained less Zr, K and Rb, and more Fe, Mg, and Ni than the Apollo XI samples. The crystalline rocks show somewhat greater variations in Mg, Ni, and Cr content, but — in spite of their greater variability in mineral content — they appear to be derived from a very similar magma. Only one rock had a great deal more Si, K, Rb, Pb, Zr, Y, Yb, U, Th and Nb than had been encountered previously [7].

New elements such as the transuranium elements and super-heavy nuclei were also sought in the lunar material. Since the Moon has no atmosphere, cosmic ray nuclei can be imbedded in the outer layers. For ^{244}Pu and ^{247}Cm, extremely small concentrations of less than 10^{-17} g per gram of Moon material could be reported. Such measuring sensitivity had not previously been attained.

The natural isotope abundances of many elements such as C, N. O, Si, S and others show no greater deviations than are common in Earth samples. The lighter isotopes are usually less abundant, which could be a result of still unknown fractionation processes.

Hydrogen* extracted from the lunar dust in an exception. Its abundance is smaller than in terrestrial hydrogen by a factor of at least 8 [8]. Since it is of solar origin, as is shown below, we can establish a valuable conclusion on the deuterium content of the solar corona.

Physics of the Lunar Surface

Since the Moon has no atmosphere, all types of radiations, electromagnetic waves, low energy solar wind particles, solar and galactic components of cosmic radiation, and even interplanetary dust and meteorites can arrive unhindered at the lunar surface.

We can utilize the processes taking place in this way to learn somewhat /187
more about the radiation itself or about the temporal changes of the lunar

*Translator's Note: The context implies this should be deuterium.

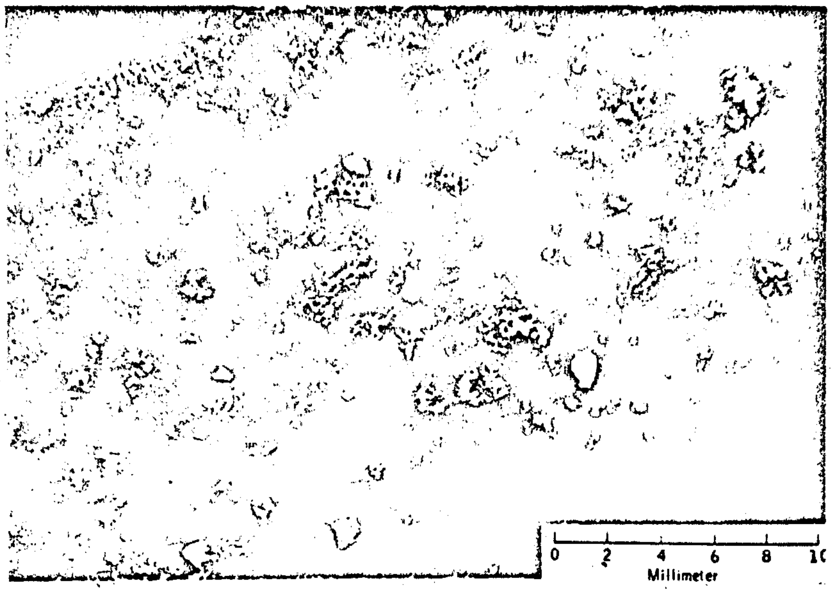

Figure 13. The surface of a Moon agglomerate. Many small impact craters from micrometeorites can be detected. Most of the craters are vitrified.

surface, and in particular, about the magnitude of the turnover rates for the individual layers. From the natural radioactive materials and their daughter substances, we can date the rock-forming process and learn something about the history of the formation of the Moon.

Meteorite Bombardment

When studying the lunar rocks, it is striking that most of them are round on one side. This can be seen clearly even in photographs made on the lunar surface. It seems that there is a process which causes erosion. On looking more closely, small impact craters can be seen on the surfaces. Figure 13 shows such a surface which is enough like a lunar landscape to be confused for it. Even under the microscope and the highest electron-microscopic enlargements, such microcraters may be detected with diameters down to 0.1 μm (Figure 14).

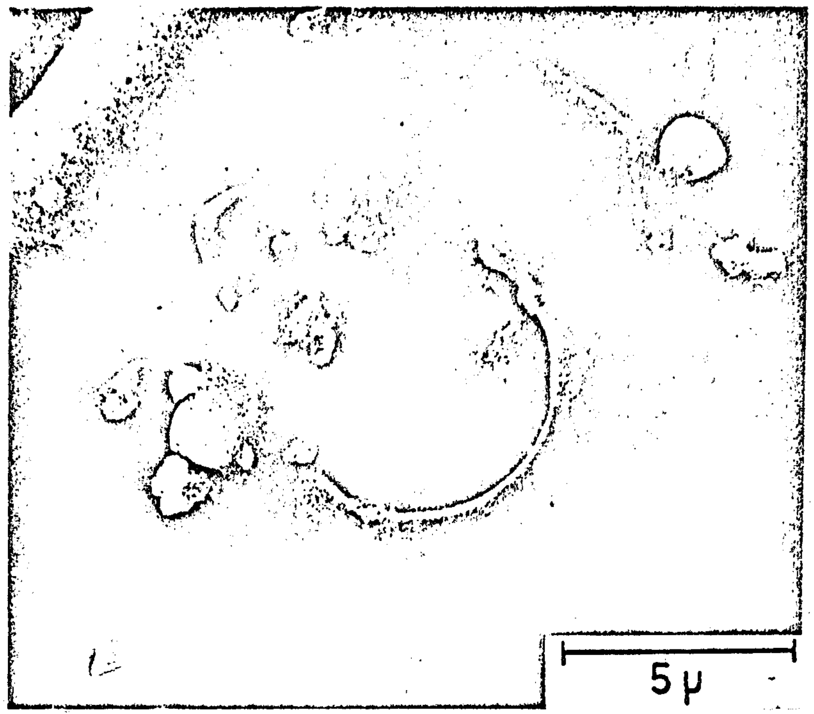

Figure 14. A microcrater greatly enlarged with the scanning electron microscope. The impact site is in the center, from which the material was vaporized away. The material is fractured radially due to the mechanical stress. (Photo: Max Planck Institute for Nuclear Physics, Heidelberg).

The following crater densities were found on the lunar rocks [9]: /188

6 craters per cm^2 with a diameter $\geq$ 1 mm

100 craters per cm^2 with a diameter $\geq$ 0.15 mm

$2 \cdot 10^5$ craters per cm^2 with a diameter $\geq$ 0.002 mm

The crater density decreases exponentially with particle size. The small craters, to be sure, are much too rare in comparison with the expected planetary dust flux. They are apparently covered with dust by the continuing turnover, or erased by erosion. The erosion process is assumed to comprise new micrometeorite impacts, as well as wear from "dust storms" from adjacent impacts of larger bodies. After a period of 10^4 a, sort of equilibrium appears, because all the rocks studied so far (Apollo XI and XII) have the same density distribution for microcraters with diameters less than 1 mm.

Larger craters have a longer lifetime, and craters beyond 1 m in diameter /189 have remained since the origin of the dust layer in the Sea of Tranquility. Their abundance correctly shows the incidence rate for larger bodies. From this, together with satellite measurements, we can extrapolate the true incidence rate for smaller particles. If one were to place a sheet of 1 m^2 area (or one astronaut) on the lunar surface, then on the average it would be 30,000 years before it was struck by a particle of 1 mm diameter. In comparison, this area would be struck by a 0.1 mm particle every 30 years, or by a 0.001 mm particle every 20 minutes.

The object of crater studies in the Moon rocks is to find out whether material from the impacting projectiles is to be found in the vicinity of the craters, and whether a conclusion can be reached about the chemical composition of interplanetary material. From the ratio of diameter to depth, we can attempt to determine the velocity of the impacting particle. For this purpose, simulation experiments were performed in the laboratory. Dust particles were electrically charged and accelerated with a high-voltage generator to 40 km/sec. Figure 15 shows an artificial impact crater in Moon rock produced in this way.

Cosmic Radiation

The highly energetic particles of cosmic radiation cause nuclear reactions on the lunar surface, just as in meteorites (see the contribution from H. Wänke, Yearbook, 1966). The depth of penetration depends on the energy and on the type of particle. For the protons of the galactic component this amounts to about 1 m. For the solar components, with an average proton energy of some 100 MeV it is only a few centimeters.

As we have learned from meteorite investigations, the intensity of the galactic component has not changed more than 50% during the last 10^9 a,

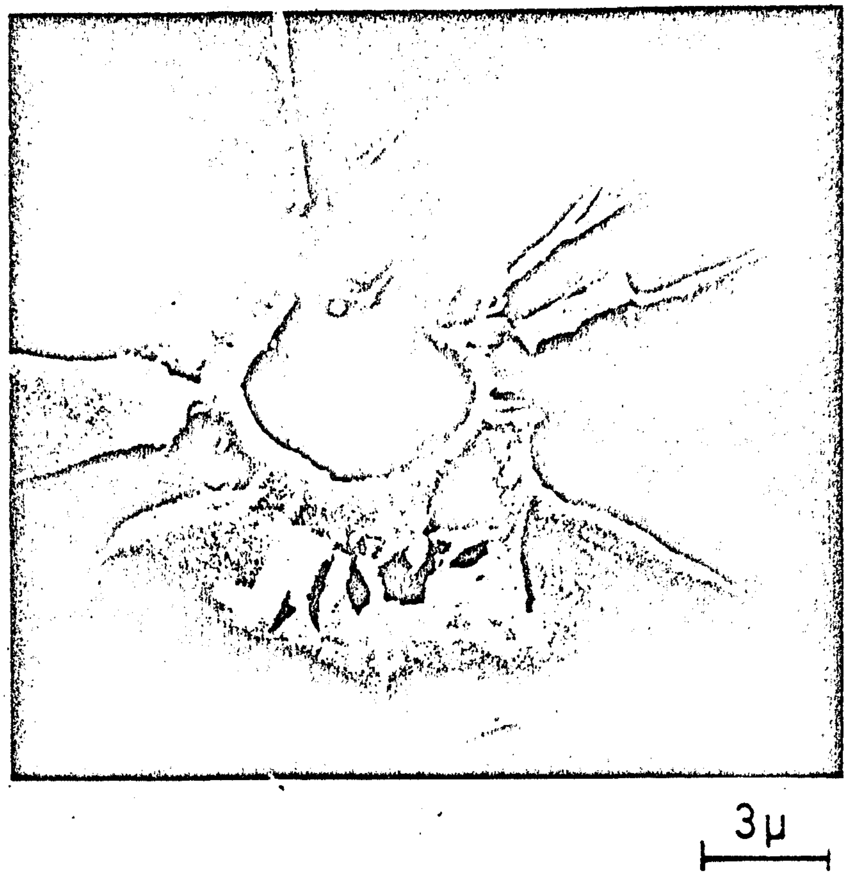

Figure 15. An iron particle has been fired at 5 km/sec into quartz glass in the laboratory. The impact crater shows a structure very similar to those in the lunar material. (Photo: Max Planck Institute for Nuclear Physics, Heidelberg).

so that we can consider it as a radiation source which is practically constant with time. The nuclear reactions produced by it can be described as follows: a high-energy particle which strikes an atomic nucleus emits a cascade of neutrons, protons, and π-mesons in the forward direction. In this way the energy is transferred to the nucleus, and it becomes hot. The excitation energy is given off by vaporizing off other particles such as n, p, d, t, ^{3}He, and ^{4}He, as well as by splitting off nuclear fragments. The reaction products may be many light new nuclei, along with residual nuclei with masses smaller than those of the starting particles. At a constant radiation intensity, one

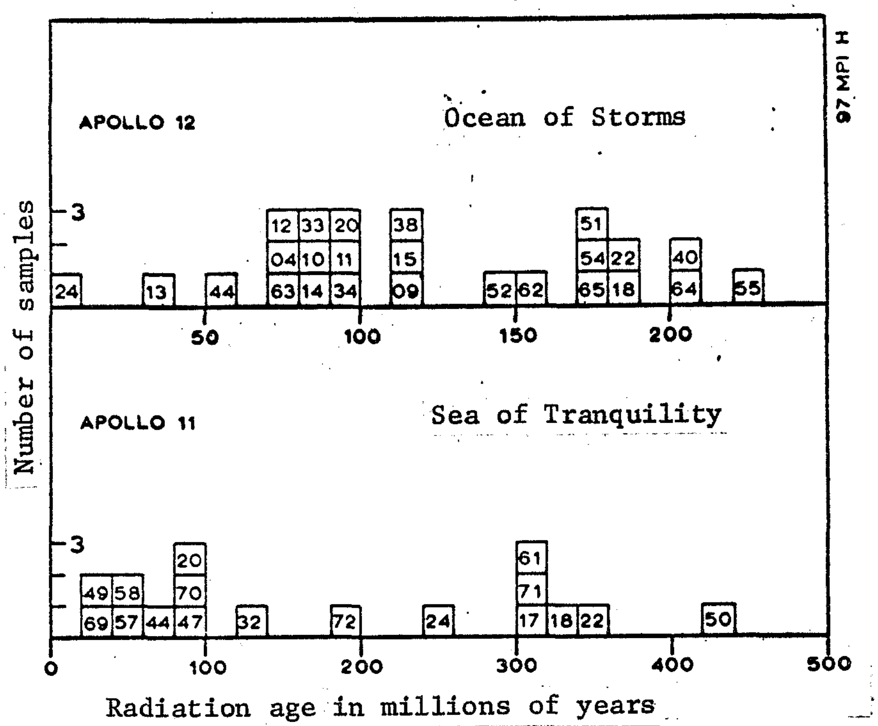

Figure 16. Histogram of the radiation ages of the crystalline Apollo XI and XII rocks. Each square represents one stone. The measured age indicates how long the rock was in the upper layer of about 1 m thickness [12]. (The numbers indicate the NASA sample numbers.)

can calculate the duration of action of the cosmic radiation from the amount of the reaction products and the production rate. ^{3}He, ^{21}Ne and ^{38}Ar have proved to be suitable isotopes. To determine the production rate, one uses a radioactive isotope such as ^{22}Na, which has a half-life of 2.6 years. The ^{22}Na nuclei are in radioactive equilibrium. That is, the number of those newly formed is equal to the number which decompose. The relative production rates of various stable and radioactive isotopes can be measured with high- /191
energy accelerators. The ratio of a stable to a radioactive pair, considering the relative production rates, is then a direct measure of the radiation time.

A large number of radioactive and stable spallation products were measured in the Moon rocks: ^{3}H, ^{7}Be, ^{10}Be, ^{22}Na, ^{26}Al, ^{36}Cl, ^{44}Ti, ^{46}Sc,

^{48}V, ^{49}V, ^{52}Mg*, ^{53}Mn, ^{54}Mn, ^{55}Fe, ^{56}Co, ^{57}Co, ^{59}Ni (radioactive) and ^{3}He, ^{21}Ne, ^{36}Ar, ^{38}Ar, ^{78}Kr, ^{83}Kr, ^{124}Xe, ^{126}Xe (stable) [8, 10, 12]. The production rate for ^{3}He appears as 10^{-8} cm^3/g per million years. The radiation ages determined in the lunar laboratory are shown in Figure 16 for Apollo XI and XII. The ages indicate how long the rocks have been in the upper meter of the lunar surface. For the Sea of Tranquility, the values are between 20 and 500 million years. During this time, apparently, rocks from the basic stone have been thrown irregularly into this region from impacts in the neighborhood. In the Sea of Storms, the radiation ages are only half as /192 great. Perhaps that region was accidentally overwhelmed by a thick dust covering 200 million years ago.

The Moon dust can also be dated with the same methods. On the surface, of course, the particles are enriched by the gases from the solar wind. These are superimposed on the spallation products and can only be removed by etching. The ages found for the Apollo XI lunar dust are likewise very high, lying between 300 and 500 million years [8, 13]. For a dust thickness of several meters, one arrives at a very small turnover rate of only 1 centimeter per million years. Thus, the footprints of the astronauts can still be found by Moon visitors after some millions of years.

The solar component also produces similar nuclear reactions. As most of the particles have less energy, they penetrate only into the upper centimeter layer, and correspondingly fewer neutrons are knocked out of the target nuclei. Particularly increased activities of ^{22}Na, ^{26}Al, ^{53}Mn, ^{55}Fe, ^{56}Co and ^{57}Co isotopes were found close under the target nuclei. These clearly reflect solar activity. A flare on 19 April 1969, the intensity of which was followed with satellites, presumably induced the high activity of some short-lived isotopes (^{56}Co, ^{57}Co, ^{54}Mn, ^{55}Fe) [10].

*Translator's Note: This correctly should be ^{52}Mn.

Several long-lived isotopes also have a greater abundance, in comparison with meteorites. Thus, it appears that there have been solar flares for millions of years. In meteorites, this layer with the reaction products from the solar component has been lost by burning away in the Earth's atmosphere. Professors Wänke and Bergmann and their co-workers have contributed actively to these problems, as well as to the chemical analyses [11].

Solar Wind

Still another type of particle radiation comes from the Sun, the so-called solar wind. It was predicted as early as 1951 by Biermann [14] on the basis of comet observations. Because of the high temperature in the solar corona, a plasma escapes steadily into planetary space at about 500 km/sec. If it strikes a comet with a plasma tail, then the tail is deflected radially away from the Sun. The solar wind can strike without hindrance on the Sun-side of the lunar surface, as the magnetic field of the Moon is extremely weak. In the terrestrial magnetic field it is deflected, and flows around the magneto- /193 sphere at about 10 Earth radii distance.

During both lunar landings, the solar wind particles have been trapped directly with a solar sail, and have been analysed in the laboratory.

The measurements were performed in Switzerland, and were very difficult, as minute amounts of lunar dust affected the measurements. Nevertheless, they were able to determine a particle flux for ^4He of $6.5 \cdot 10^6$ $^4He/cm^2$ sec. This agrees well with the expected value [15].

As already indicated, the Moon samples themselves contain much larger amounts of solar wind. The mean energy of the protons in the solar wind is about 1 KeV, and their penetration depth is some 100 Å. Moon dust, agglomerates, and even the surfaces of crystalline rocks are fully charged with solar wind particles. Moon dust from Apollo XI, and agglomerates, contained about 1 cm^3 H_2/g, 0.2 cm^3 He/g, $2 \cdot 10^{-3}$ cm^3 Ne, $4 \cdot 10^{-4}$ cm^3 Ar, $2 \cdot 10^{-7}$ cm^3 Kr and 10^{-7} cm^3 Xe per gram. The dust samples from Apollo XII contained about one-third as much solar wind. It can easily be shown that these gases stick on the surfaces of the particles.

The gas content increases with decreasing size in sieve fractions of dust samples, and is approximately proportional to $\frac{1}{r}$, the ratio of surface to volume. With successive etchings it can also be shown that these gases are enriched in the outermost layers of a few μm thickness. These studies, among others, were a principal object of the work of the Max Planck Institute in Mainz [8] and Heidelberg [13]. No solar wind can be found in the interiors of the crystalline rocks.

In Heidelberg, we developed a new type of technique which saves material and is especially suited for these studies.

A volume of about 100 μ^3 is melted and degassed with a fine electron beam a few microns in diameter in a microprobe. The chemical composition is determined by means of the characteristic x-ray spectrum. The helium emission is determined simultaneously with a mass spectrometer. By scanning the surface of a lunar sample, one can determine which side was turned toward the Sun (Figure 17). The helium content can be determined for various mineral types in agglomerates or dust preparations. For this analysis, 800 mineral grains were selected. Together, they weighed less than one milligram! The results are extremely interesting, and give some indication of the history of the lunar dust.

Through annealing the dust granules at the lunar surface, where temperature differences from -150° to +120° C prevail in the outside layers, the noble gases are partly lost, or they diffuse into the interior of the mineral grains. Helium diffuses more easily than neon and argon. From the differing /194
penetration depths of these gases (4.4 μ; 2.1 μ; and 1.4 μ for He, Ne and Ar) we can calculate that the dust grains were exposed to the solar wind for an average of 10,000 years.

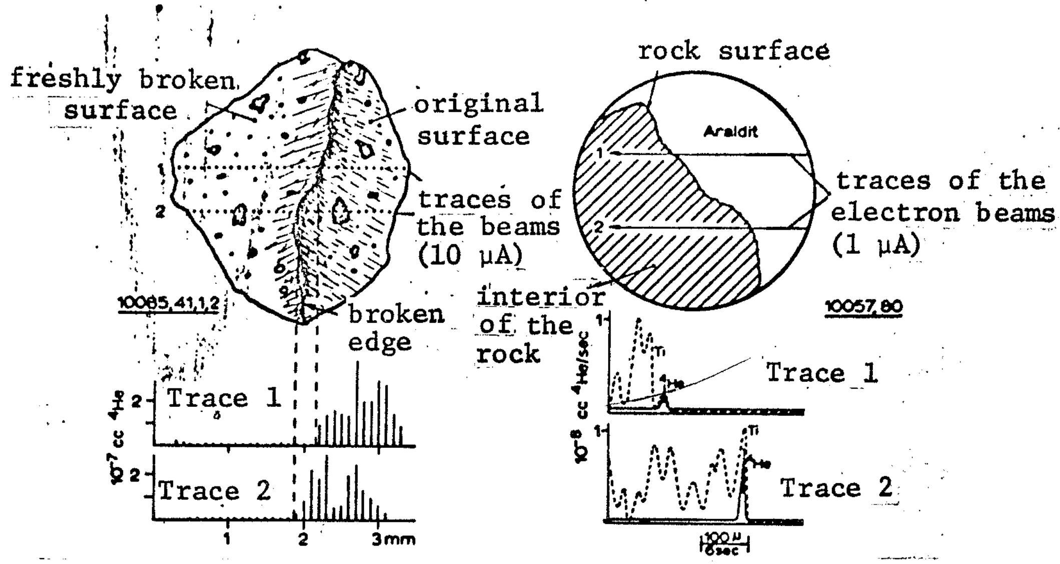

Figure 17. A Moon rock is scanned with an electron beam. The left rock has one surface charged with the solar wind, and one fresh fracture surface. The solar wind helium can be demonstrated only on the original surface (below). Right: the rock is cut perpendicularly to the surface and embedded. When the electron beam is passed through steadily, only the thin surface layer gives off helium.

The annealing also explains why more He is present in the titanium-rich minerals, in ilmenite and ilmenite-rich agglomerates, than in glass, pyroxene and plagioclase. The noble gas diffuses out of the latter minerals more easily.

Thus, we cannot expect the gases in the lunar samples to record the correct composition of the solar corona. Presumably the lighter gases are lost preferentially. The isotope abundances show interesting deviations from the noble gases in the atmosphere.

In helium, ^{3}He is present in the proportion $^{4}He/^{3}He \approx 2{,}800$. The $^{20}Ne/^{22}Ne$ ratio is 13, much larger than the atmospheric value of 9.5. The isotopes ^{134}Xe and ^{136}Xe are somewhat more abundant in atmospheric Xe than in the solar wind, probably because of Xe from the spontaneous fission of terrestrial uranium. The $^{40}Ar/^{36}Ar$ should be smaller than 0.01 according to considerations of nuclear systematics. Much larger values are found in the solar wind: 1.0 for Apollo XI and 0.5 for Apollo XII. The clear difference /195 in the two dust samples already indicates that the ^{40}Ar is derived from a source other than the solar wind. It was proposed that the degassing of the lunar material produced a transient thin atmosphere of radiogenic ^{40}Ar, which was included secondarily in the lunar surface due to electromagnetic interaction with the solar wind.

We have previously encountered noble gases with such compositions and with practically exactly the same isotopic abundances in about 10 extraterrestrial meteorites.

We must assume that the gas-rich meteorites have also been irradiated by the solar wind in a similar way. Wänke [16] proposed this hypothesis, and it has been confirmed by the analyses of the Moon samples. In the future we can investigate the solar wind just as well in gas-rich meteorites, and use the valuable lunar material for other problems.

The Age of the Moon and of the Moon Rocks

The most interesting result from the studies of the lunar samples was the great age. Even the first provisional noble gas analyses in the lunar laboratory in Houston, which were performed by O. A. Schaeffer, J. Funkhouser, D. Bogard and the author, revealed this surprise. The K-Ar-ages are shown for both missions in Figure 18, as histograms. The values for Apollo XI scatter around 3.6, and for Apollo XII — around 2.5 billion years. The low values can be explained by gas losses due to the high surface temperature on the Moon. Turner [17] has determined these gas losses with an ingenious method. The corrected ages for the Sea of Tranquility were 3.6 billion years. The starting time of this radioactive clock is the latest complete degassing (fusion of the magma), and the time measurement begins on cooling off at about 200° C if the rock holds the radiogenic ^{40}Ar in the crystal

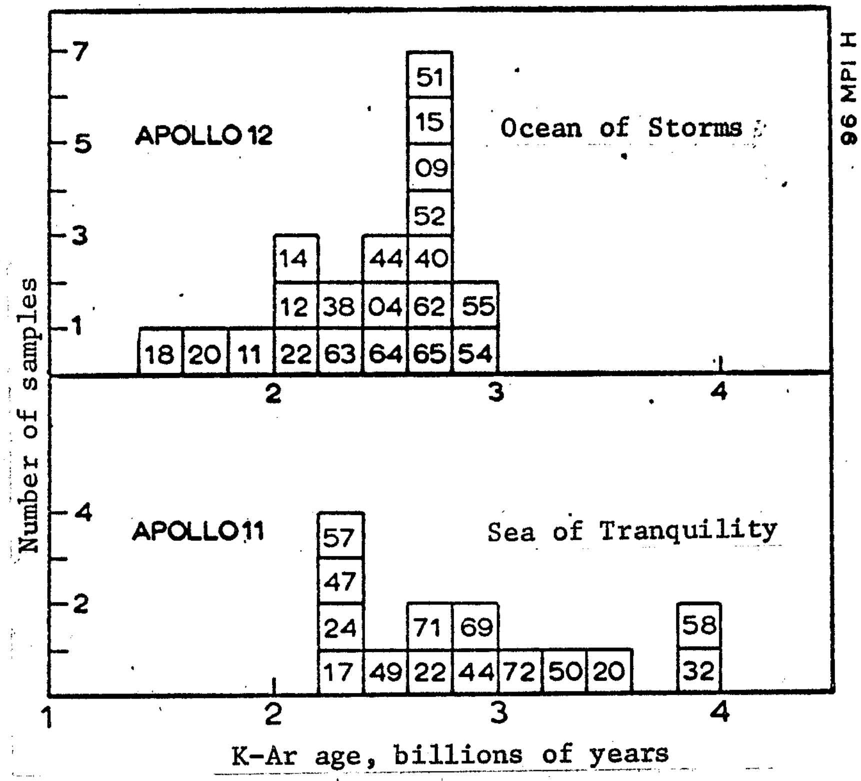

Figure 18. Histogram of the K-Ar ages of the crystalline rocks from Apollo XI and XII. (The numbers indicate the NASA sample numbers [12].)

lattice. Since then, the K-Ar results for the Apollo XI samples have been confirmed by extremely precise isotope analyses with all the known dating methods. Confirmation for Apollo XII is still outstanding. According to the latest reports, individual Apollo XII rocks have ages up to 4.5 billion years. The results are summarized in Table 2.

The Rb-Sr and U-Pb methods date the crystallization from the magma. From mineral fractions with different ratios of mother and daughter substances, one obtains the radiogenic portion in the components with a higher concentration of mother substance.

TABLE 2. TABULATION OF AGES ACCORDING TO DIFFERENT DATING METHODS.

AGES OF LUNAR SAMPLES IN BILLIONS OF YEARS, APOLLO XI

	K-Ar (12) (17)	Rb-Sr (18)	U-Pb (19)	Pb-Pb (19)
Crystalline rocks	2,3–3,7	3,59–3,70	3,7–4,1	3,8–4,1
Dust	1,6–4,6	4,1 –4,6	4,7	4,7
Agglomerates	—	4,1	4,7	4,7

Apollo XII: K-Ar age 1.8-2.7 billion years [1].

The Rb-Sr measurements were very difficult, because the Rb content in the lunar material is extremely small. The differences in the ^{87}Sr abundances are only some 1%. Wasserburg and co-workers were the only ones able to measure this difference with sufficient precision, using an "on-line" controlled mass spectrometer technique [18].

The uranium content in the lunar samples is relatively large, and the primary lead, being a volatile element, is depleted, so that 90% of the lead content is of radiogenic origin. Thus, the composition of the primordial lead plays a subordinate role, and the U-Pb measurements likewise provide reliable crystallization ages [19].

Both methods yield 3.7 billion years for the rocks from the Sea of Tranquility which have been measured to date. One exception is the rock (10057) that gives a U-Pb age of 4.1 billion years, but a Rb-Sr age of 3.7 billion years. In comparison, the oldest terrestrial rocks are only 3.5 billion years old.

The measurements on individual components of the lunar dust are interesting. The K-Ar ages lie between 1.6 and 4.5 billion years. The lower values can be explained by gas losses. The Rb-Sr ages are between 4.1 and 4.5 billion years. Components with such great ages can apparently not be derived from the Apollo XI rocks themselves. Rather, the main portions of the dust must have been transported into the Sea of Tranquility from regions with still older rocks. It is conjectured that the mountains to the west and south of the landing site may be such a source. It is remarkable, certainly, that the chemical composition of the dust does not deviate more from that of the rock. One of the Apollo XIII objectives should be to bring back such samples from the highlands. /197

The provisional results for the rocks from the Sea of Storms are also plotted in Figure 18. Their ages are less by about 1 billion years, but it remains to be seen whether other methods will confirm these ages. In case large meltings occurred at such a late period, it will be necessary to formulate new ideas for the energy source in all hypotheses for the origin of the Moon.

As with the Earth, the true origin of the Moon as an independent body can be dated only from the Pb isotopes. The so-called Pb-Pb-age yields the time since the Pb was in combination with the uranium on the lunar surface. This is therefore identical with the formation of the uranium-rich lunar crust or with the origin of the Moon itself. The dust is a suitable, thoroughly blended average sample of the lunar surface. Its Pb-Pb-age is 4.66 billion /198 years. This agrees with the ages of the meteorites and with the Pb-Pb-age of the Earth [19].

From the Rb/Sr ratios of the Earth and the Moon, and from the primary $^{87}Sr/^{86}Sr$ ratio in the lunar dust, we can estimate that the lunar material was not mixed with terrestrial material for more than 200 million years. Otherwise, the lunar strontium would have had a greater proportion of radiogenic ^{87}Sr. The Moon, Earth, and even the meteorites apparently all formed at about the same time.

Lunar Hypotheses

It is not expected that the new results will immediately answer the question of the origin of the Moon satisfactorily, or allow existing hypotheses to be excluded with certainty. But we can take up the problem anew with better-directed questions, and attempt to revise the old concepts.

The tide theory, according to which the Moon was torn out of the more or less solid Earth crust, is not tenable in a simple form. The separation must already have taken place 4.4 billion years ago. O'Keefe suggests a fission process by which both parts proceeded on similar paths and later co-rotated. The Moon was strongly heated on the surface by strong tidal forces, so that the easily volatile components vaporized away. Chemical differentiation is supposed to have occurred in this phase.

Urey's concept, by which the Moon resulted from many captured meteorite-like bodies, cannot explain the chemical composition and the density of the Moon.

The origin of the Moon, together with the Earth as a double planet, is receiving somewhat more attention in more recent discussions. In the initial stage of our solar system, a Saturn-like ring moved around the Earth. At this time the Sun went through the phase of deuterium burning and heated the ring so strongly that the readily volatile elements escaped selectively. This model attempts to explain the difference in the densities of the Moon and Earth, and also the fractionation of the volatile elements between the Moon /199
and the Earth.

REFERENCES

1. Gentner, W. Jahrb. d. Max-Planck-Gesellschaft (Yearbook of the Max Planck Society), 1964, p. 90.

2. Ramdohr, P. and A. El Goresy. Science, Vol. 167, 1970, p. 615.

3. Patterson, J. H., A. L. Turkevich, E. J. Franzgrote and T. E. Economon. Science, 1970.

4. The Lunar Sample Preliminary Examination Team. Science, Vol. 165, 1969, p. 1211.

5. Haskin, L. A., P. A. Helmke and R. O. Allen. Science, Vol. 167, 1970, p. 487.

6. Keays, R. R., R. Ganapathy, J. C. Laul, E. Anders, G. F. Herzog and P. M. Jeffery. Science, Vol. 167, 1970, p. 490.

7. The Lunar Sample Preliminary Examination Team. Science, Vol. 167, 1970, p. 1325.

8. Hintenberger, H., H. W. Weber, H. Voshage, H. Wänke, F. Begemann, E. Vilscek and F. Wlotzka. Science, Vol. 167, 1970, p. 543.

9. Neukum, G., A. Mehl, H. Fechtig and J. Zähringer. Earth and Planetary Science Lett., Vol. 8, 1970, p. 31.

10. Shedlovsky, J. P., M. Honda, R. C. Reedy, J. C. Evans, Jr., D. Lal, R. M. Lindstrom, A. C. Delany, J. R. Arnold, H. H. Loosli, J. S. Fruchter and R. C. Finkel. Science, Vol. 167, 1970, p. 574.

11. Wänke, H., F. Begemann, E. Vilscek, R. Rieder, F. Teschke, W. Born, M. Quijano-Rico, H. Voshage and F. Wlotzka. Science, Vol. 167, 1970, p. 523.

12. Funkhouser, J. G., O. A. Schaeffer, D. D. Bogard and J. Zähringer. Science, Vol. 167, 1970, p. 561

    —. Science (in press).

13. Kirsten, T., F. Steinbrunn and J. Zähringer. Science, Vol. 167, 1970, p. 571.

14. Biermann, L. Z. Ap., Vol. 29, 1951, p. 274.

15. Bühler, F., P. Eberhardt, J. Geiss, J. Meister and P. Signer. Science, Vol. 166, 1969, p. 1502.

16. Wänke, H. Z. Naturforsch, Vol. 20a, 1965, p. 946.

17. Turner, G. Science, Vol. 167, 1970, p. 466.

18. Abee, A. L., D. S. Buinett, A. A. Chodos, O. J. Eugster, J. C. Huneke, D. A. Papanastassiou, F. A. Podosek, G. Price Russ II, H. G. Sanz, F. Tera and G. J. Wasserburg. Science, Vol. 167, 1970, p. 463.

19. Tatsumoto, M. and J. N. Rosholt. Science, Vol. 167, 1970, p. 461.

20. Papanastassiou, D. A. and G. J. Wasserburg. Earth and Planetary Science Lett., Vol. 8, 1970, p. 269.

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